Applications of the ADIFOR 3.0 Automatic Adjoint Generation Tool at the NASA Langley Research Center

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Objectives

- Apply <u>A</u>utomatic <u>Di</u>fferentiation of <u>For</u>tran (ADIFOR), version 3.0, to codes of interest for NASA
- Demonstrate ADIFOR 3.0 automatic adjoint generation capability in:
  - Aerodynamic Sensitivity Analysis (wing grid generation + computational fluid dynamics)
  - Aerodynamic Shape Optimization (Aerodynamic Sensitivity Analysis + gradient-based optimization)
  - Aerodynamic Control Effectiveness Analysis

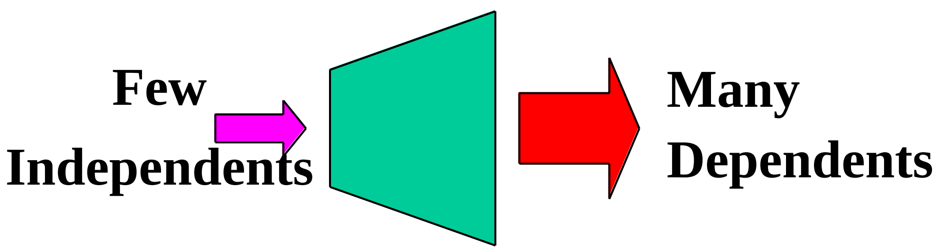
Acknowledgements

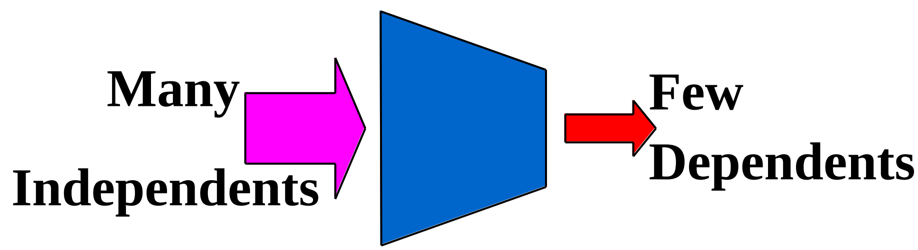
Alan Carle and Mike Fagan of Rice University
Joanne Walsh of NASA Langley Research Center (NASA LaRC)

ADIFOR 3.0 from Rice University

- Forward mode (ADIFOR)
- Chain rule of calculus
- Forward propagation of derivatives through the code
- Best for more dependent than independent variables
- Forward mode second derivatives

- Reverse Mode (“ADJIFOR”)
- Discrete adjoint formulation
- Backward propagation of adjoints through the code
- Best for more independent than dependent variables





AIAA Paper 94-2197

AIAA Paper 99-3136

AIAA Paper 98-4807

AIAA Paper 99-3136

Aerodynamic Sensitivity Analysis
Geometry and Grid Generation

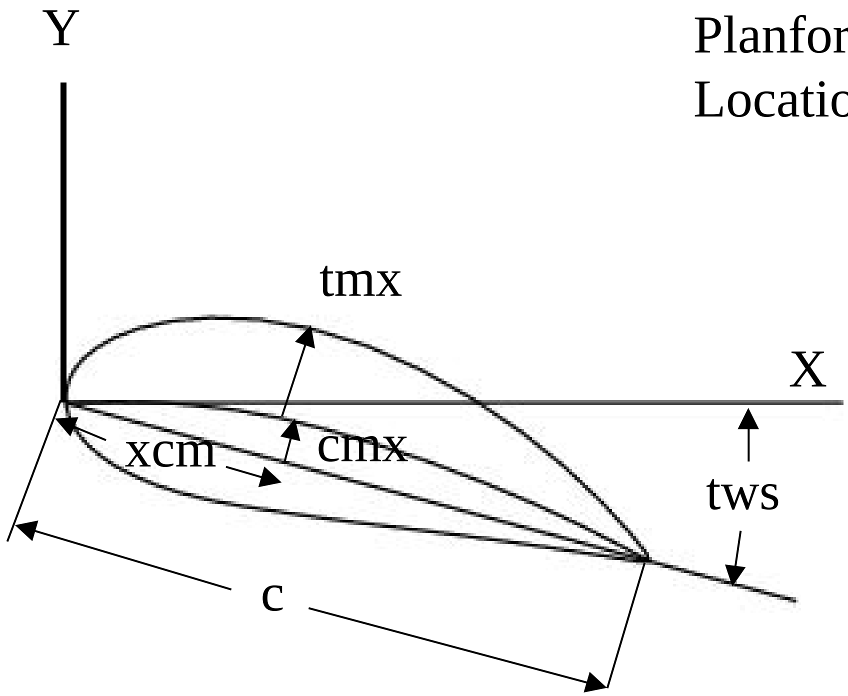
- Simple Fortran wing geometry and grid generation code (MYGRID) created for ADIFOR studies
  - **Swept, tapered transport-like wing planforms**
  - **NACA four digit airfoil series wing sections**
  - **Single-block grids generated; split for parallel flow solver execution**
  - **Grid quality was low in consideration**
  - **Many shape design variables (DV) desired for adjoint studies**
- ADIFOR 3.0 generated MYGRID.ADJ code computes <u>exact</u> surface and volume grid adjoints

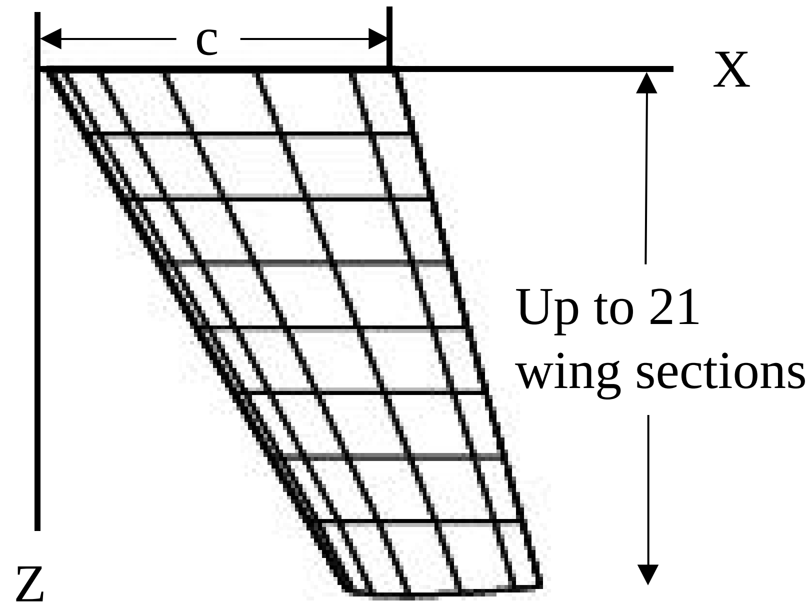
Aerodynamic Sensitivity Analysis
Computational Fluid Dynamics (CFD)

- **CFL3D** code by Thomas, Rumsey, and Biedron of NASA LaRC
  - **Iteration required to solve the Euler / Navier-Stokes flow equations in conservation form**
  - **Numerous grid, solver, and convergence acceleration options**
  - **Sequential and parallel code versions used**
- ADIFOR 3.0 generated CFL3D.ADJ code computes the <u>exact</u> lift-to-drag ratio (wing efficiency) adjoint
  - **Initial differentiation excluded the viscous flow modeling routines**
  - **Automatically generated code required enormous disk storage (33GB)**
- The manually implemented Iterated Reverse Mode (IRM) reduces disk storage by saving only the converged "steady-state" solution information

Aerodynamic Sensitivity Analysis
Wing Design Variables (DVs) Definition

Planform DVs: X, Y, Z of each leading edge Location and each section chord (c)





Section DVs: maximum thickness (tmx), maximum camber (cmx), x-location of maximum camber (xcm), and twist angle (tws) for each section

Aerodynamic Sensitivity Analysis

Demonstrational Problem

- Volume grid sizes: 425, 2673, 18785, and 276705 points
- Point-matched wing grids
- Steady, inviscid, transonic flow around 3-D wing
- One output function (the wing lift-to-drag ratio)
- Up to 168 independent variables (wing shape parameters)

Target Problem

- Volume grid sizes: 400,000 (inviscid wing)
- Patched and overset grids
- Time dependent viscous flow around 3-D aircraft configuration
- Multiple output functions (objective + flow-dependent constraints)
- Up to 500 independent variables (aircraft shape parameters)

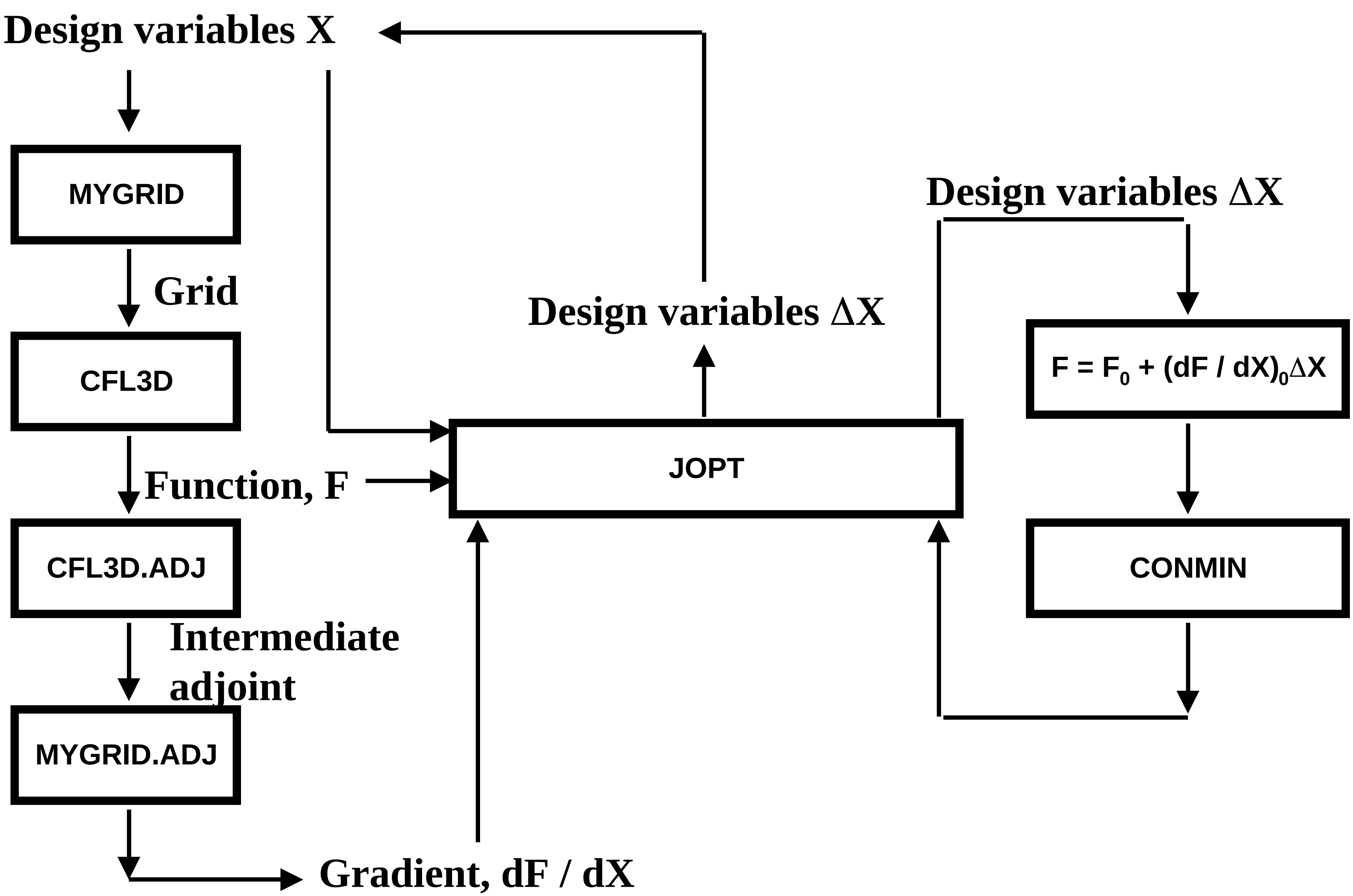
Aerodynamic Shape Optimization

Gradient-Based Optimization

- JOPT = CONMIN + first-order Taylor series approximation to the nonlinear optimization problem, based upon function and gradient
- Optimization objective - minimize -(CL / CD), or maximize (CL / CD)
- Up to 168 design variables (8 DV per section, 21 wing sections)
- DV bounds and optimization move limits imposed
- Unconstrained optimizations and geometry / grid generation executed on workstation
- Aerodynamic function and gradient execution on up to 33 processors of a NASA Ames SGI Origin 2000

Aerodynamic Shape Optimization

Optimization Flowchart

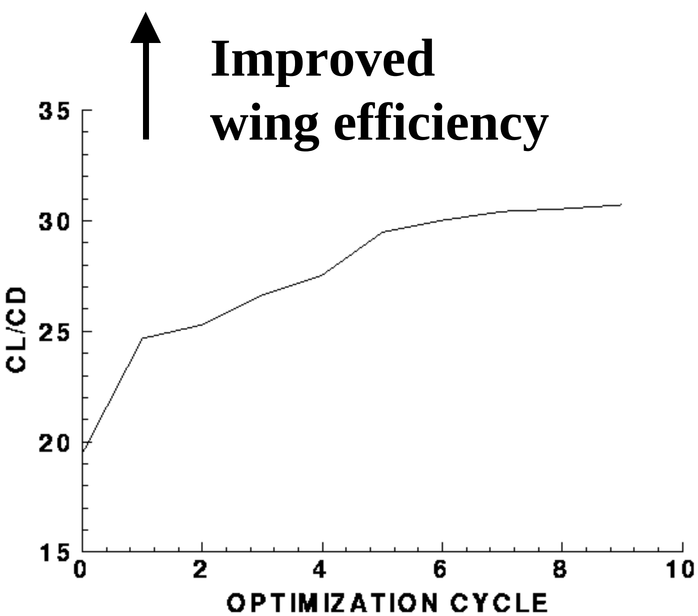


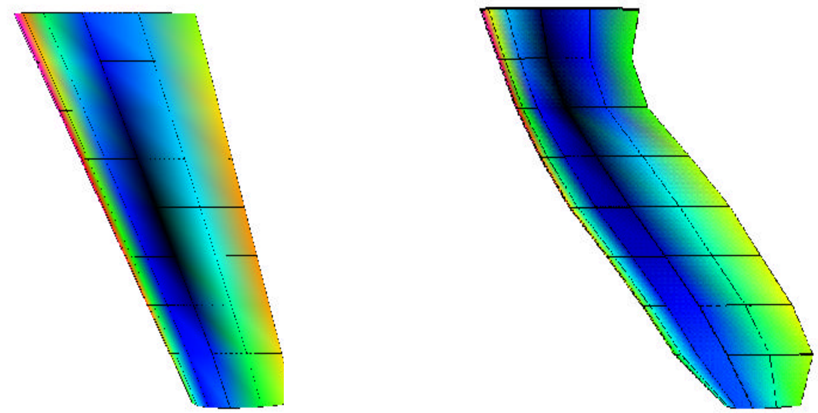
Aerodynamic Shape Optimization

Planform and Thickness Optimization Results

M = 0.84, α = 3.06 degrees, 276705 grid points,

21 wing sections, 9 optimization cycles





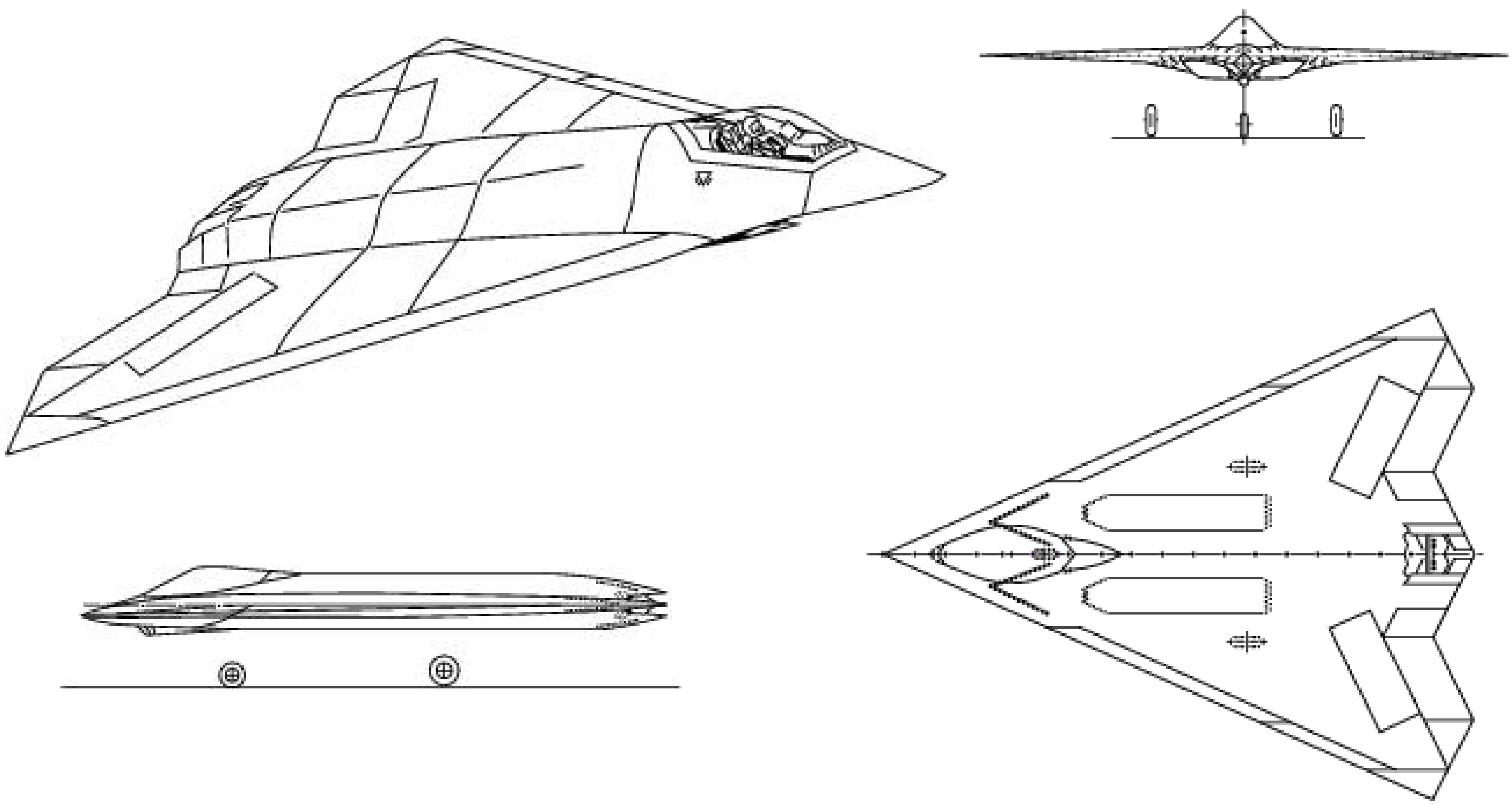
Baseline wing

“Optimized” wing

Aerodynamic Control Effectiveness Analysis
Computational Fluid Dynamics (CFD)

- PMARC code from NASA Ames Research Center
  - **Iteration required to solve potential flow equations**
  - **Inviscid, irrotational, and incompressible flow**
  - **Boundary layer and compressible flow corrections available; not used**
  - **Full 3-D aircraft configuration modeled**
- ADIFOR 3.0 generated PMARC.ADJ code computes the <u>exact</u> adjoints of three body axis moments with respect to thousands of discrete surface shape changes
- "Black-box" automatic adjoint code generation
  - **New ADIFOR 3.0 user trained and generating code within days**
  - **Execution through entire iteration process**
  - **No IRM techniques employed**
  - **Manageably large disk file generated**

Aerodynamic Control Effectiveness Analysis
Lockheed-Martin Tactical Aircraft Systems
Innovative Control Effectors (ICE) Configuration



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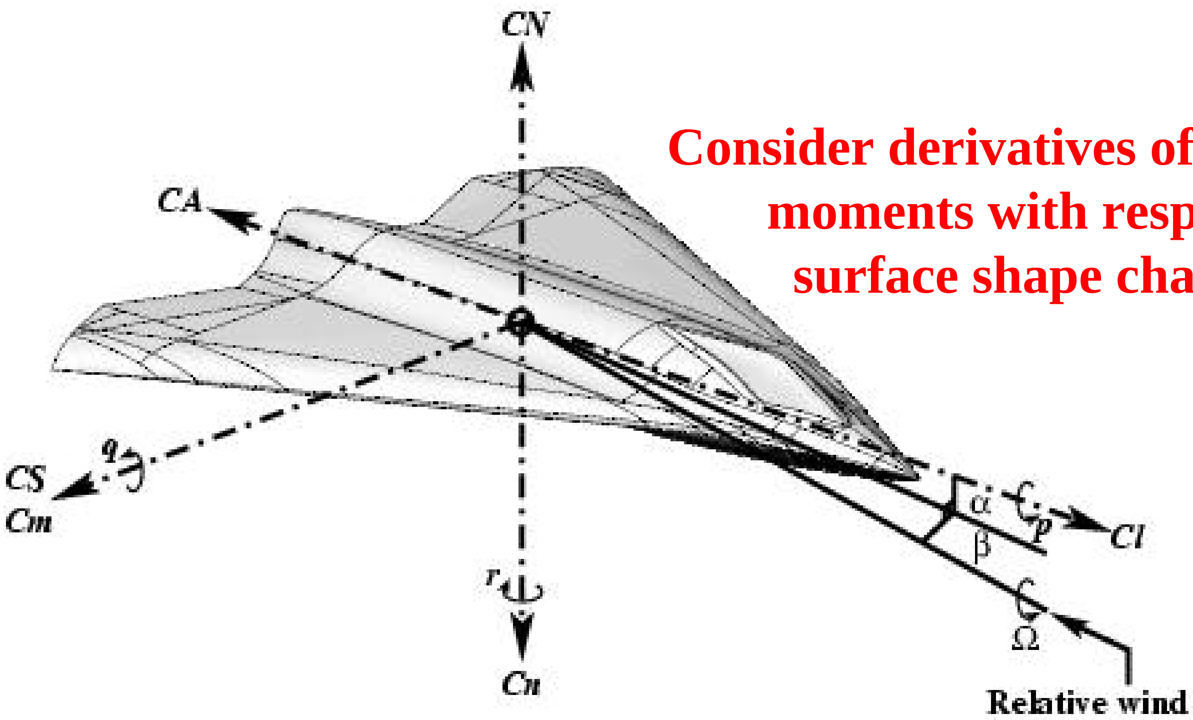
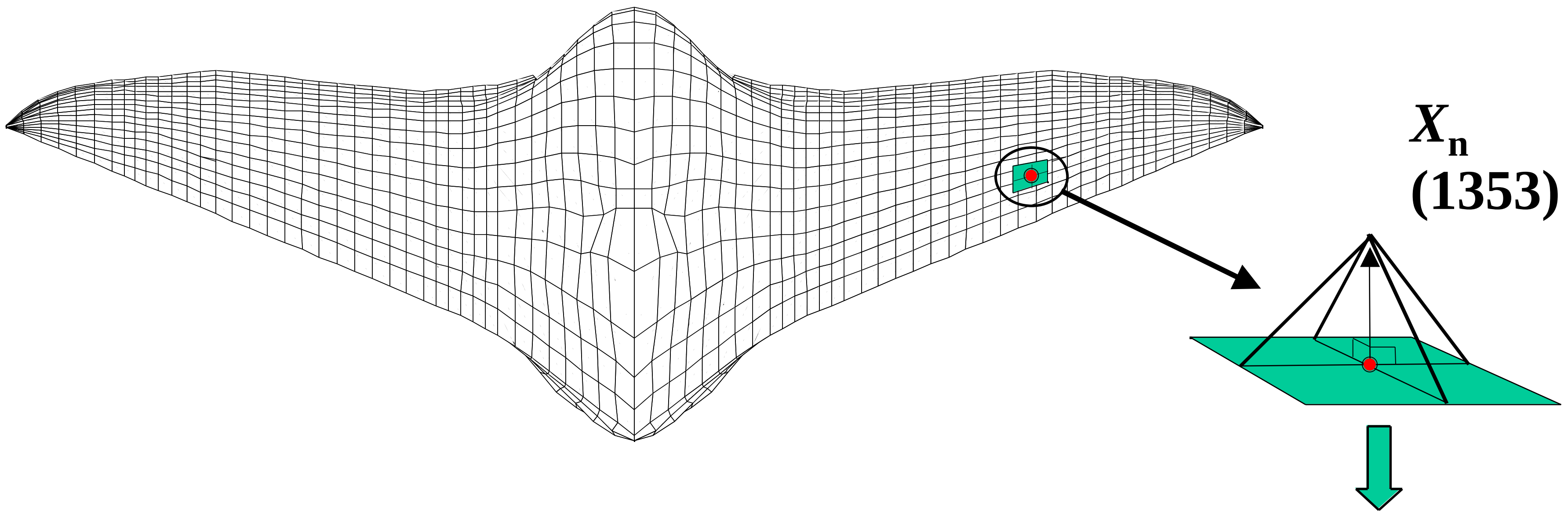


Consider derivatives of body axis moments with respect to surface shape changes

AIAA Paper 99-3136 discusses derivatives of forces and moments with respect to angle of attack (α) and angle of sideslip (β)

Aerodynamic Control Effectiveness Analysis
Derivative Definition



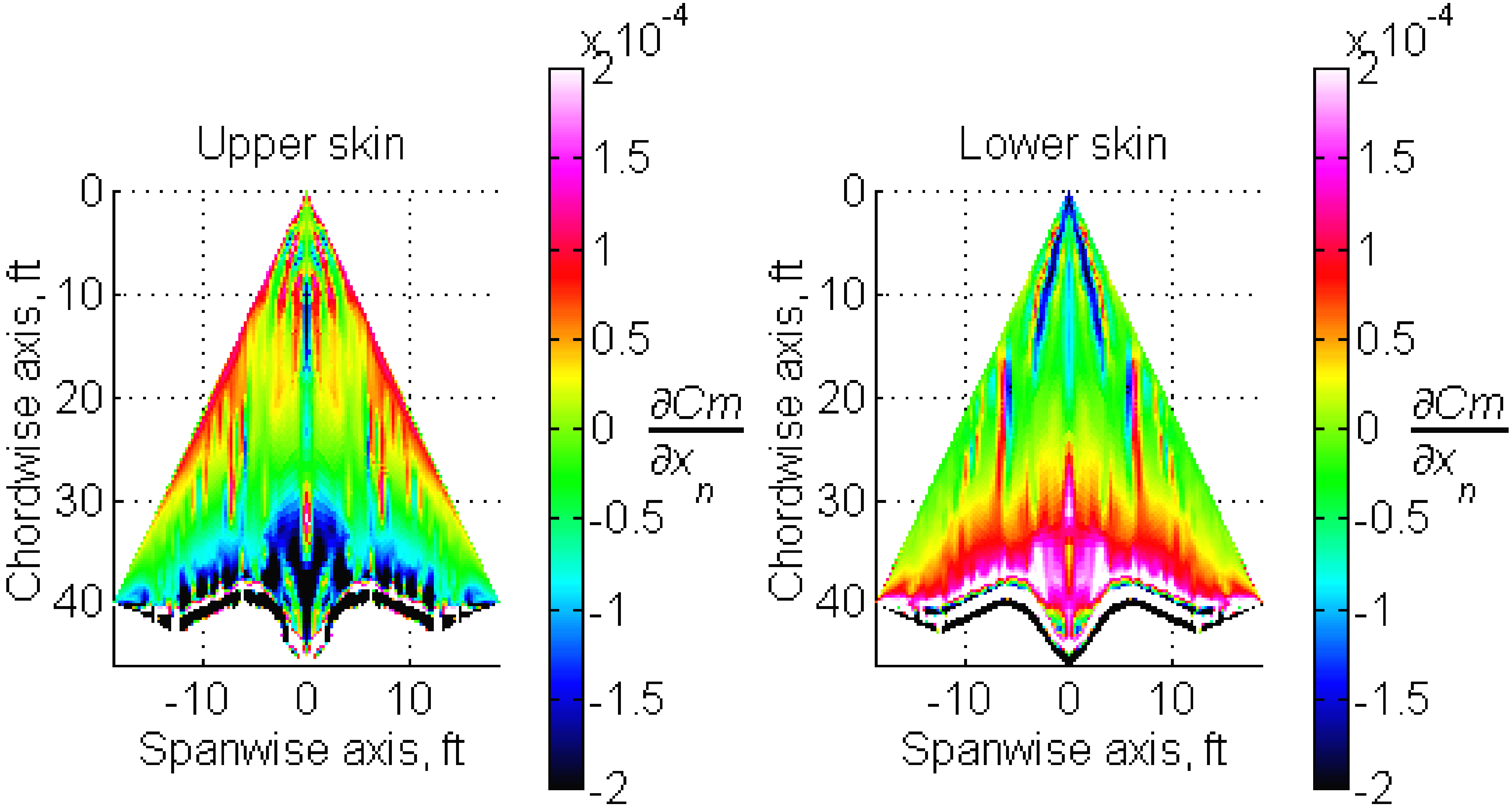
Sensitivities

- Derivatives of pitch, roll, and yaw moment coefficients with respect to a displacement of 1353 discrete surface grid points normal to the surface
- Coarse resolution surface grid sensitivities interpolated over the configuration for plotting

Aerodynamic Control Effectiveness Analysis

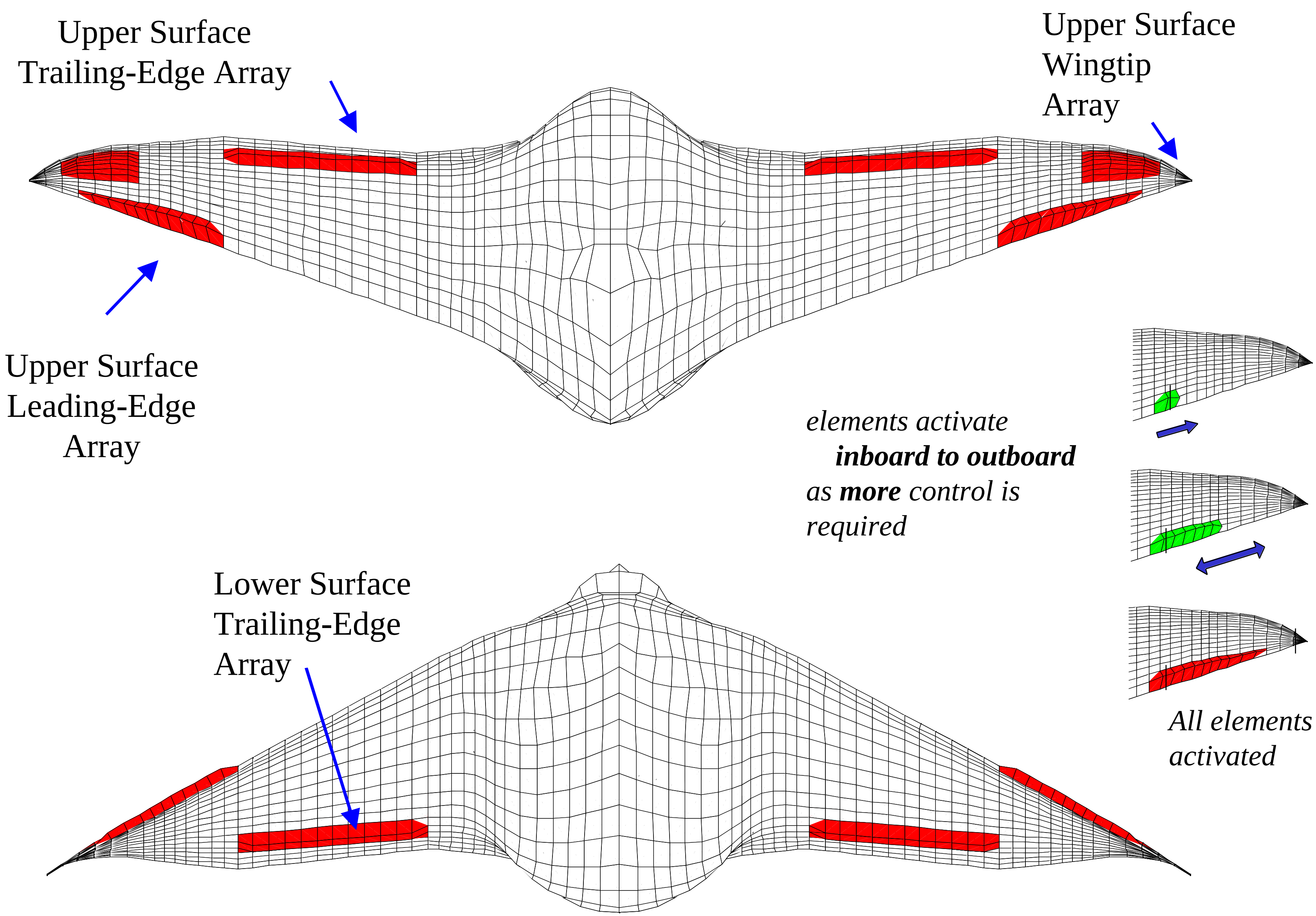
Pitch Control Effectiveness Sensitivity Contours

(Incompressible Flow, α=4.39)



Aerodynamic Control Effectiveness Analysis

Most Promising Designs (Used in Control Law Simulation)



Concluding Remarks

- ADIFOR 3.0 automatically generated adjoint code has been used in aerodynamic sensitivity analyses, aerodynamic shape optimization, and a control effectiveness analysis at NASA LaRC
- ADIFOR 3.0 generated CFL3D.ADJ adjoint code requires the execution time of about 6 to 20 function evaluations
- The Iterated Reverse Mode (IRM) technique significantly reduces the computer disk storage of adjoint code for iterative solutions
- ADIFOR 3.0 generated CFL3D.ADJ adjoint code only requires about Kbytes of RAM and about 32 Kbytes disk per grid point; enables target problem to be solved on moderate parallel computer
- Use of ADIFOR 3.0 generated adjoint sensitivities enabled the development of an interactive control selection and evaluation tool